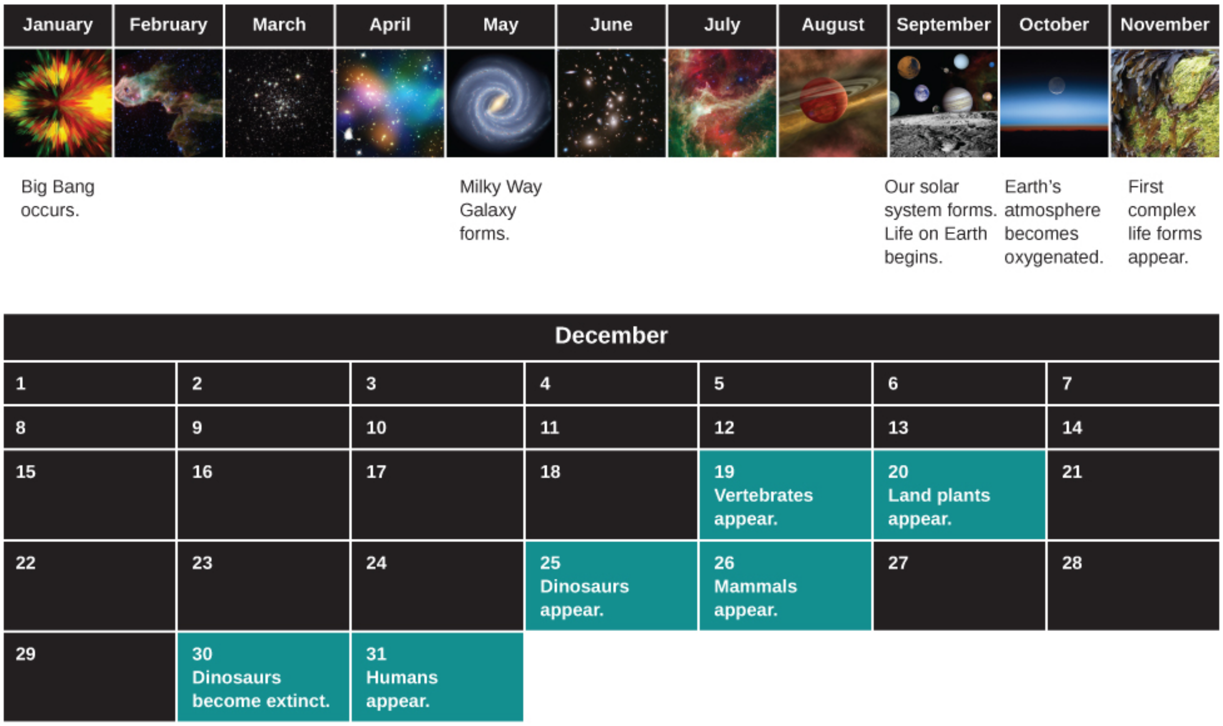
Derived copy of A Conclusion and a Beginning with added exercises

If you are new to astronomy, you have probably reached the end of our brief tour in this chapter with mixed emotions. On the one hand, you may be fascinated by some of the new ideas you’ve read about and you may be eager to learn more. On the other hand, you may be feeling a bit overwhelmed by the number of topics we have covered, and the number of new words and ideas we have introduced. Learning astronomy is a little like learning a new language: at first it seems there are so many new expressions that you’ll never master them all, but with practice, you soon develop facility with them.

At this point you may also feel a bit small and insignificant, dwarfed by the cosmic scales of distance and time. But, there is another way to look at what you have learned from our first glimpses of the cosmos. Let us consider the history of the universe from the Big Bang to today and compress it, for easy reference, into a single year. (We have borrowed this idea from Carl Sagan’s 1997 Pulitzer Prize-winning book, *The Dragons of Eden*.)

On this scale, the Big Bang happened at the first moment of January 1, and this moment, when you are reading this chapter would be the end of the very last second of December 31. When did other events in the development of the universe happen in this “cosmic year?” Our solar system formed around September 10, and the oldest rocks we can date on Earth go back to the third week in September ([link]).
Charting Cosmic Time.



On a cosmic calendar, where the time since the Big Bang is compressed into 1 year, creatures we would call human do not emerge on the scene until the evening of December 31. (credit: February: modification of work by NASA, JPL-Caltech, W. Reach (SSC/Caltech); March: modification of work by ESA, Hubble and NASA, Acknowledgement: Giles Chapdelaine; April: modification of work by NASA, ESA, CFHT, CXO, M.J. Jee (University of California, Davis), A. Mahdavi (San Francisco State University); May: modification of work by NASA, JPL-Caltech; June: modification of work by NASA/ESA; July: modification of work by NASA, JPL-Caltech, Harvard-Smithsonian; August: modification of work by NASA, JPL-Caltech, R. Hurt (SSC-Caltech); September: modification of work by NASA; October: modification of work by NASA; November: modification of work by Dénes Emőke)

Where does the origin of human beings fall during the course of this cosmic year? The answer turns out to be the evening of December 31. The invention of the alphabet doesn’t occur until the fiftieth second of 11:59

p.m. on December 31. And the beginnings of modern astronomy are a mere fraction of a second before the New Year. Seen in a cosmic context, the amount of time we have had to study the stars is minute, and our success in piecing together as much of the story as we have is remarkable.

Certainly our attempts to understand the universe are not complete. As new technologies and new ideas allow us to gather more and better data about the cosmos, our present picture of astronomy will very likely undergo many changes. Still, as you read our current progress report on the exploration of the universe, take a few minutes every once in a while just to savor how much you have already learned.

For Further Exploration

Books

Miller, Ron, and William Hartmann. *The Grand Tour: A Traveler's Guide to the Solar System*. 3rd ed. Workman, 2005. This volume for beginners is a colorfully illustrated voyage among the planets.

Sagan, Carl. *Cosmos.* Ballantine, 2013 [1980]. This tome presents a classic overview of astronomy by an astronomer who had a true gift for explaining things clearly. (You can also check out Sagan's television series *Cosmos: A Personal Voyage* and Neil DeGrasse Tyson's current series *Cosmos: A Spacetime Odyssey.*)

Tyson, Neil DeGrasse, and Don Goldsmith. *Origins: Fourteen Billion Years of Cosmic Evolution.* Norton, 2004. This book provides a guided tour through the beginnings of the universe, galaxies, stars, planets, and life.

Websites

If you enjoyed the beautiful images in this chapter (and there are many more fabulous photos to come in other chapters), you may want to know

where you can obtain and download such pictures for your own enjoyment. (Many astronomy images are from government-supported instruments or projects, paid for by tax dollars, and therefore are free of copyright laws.) Here are three resources we especially like:

- Astronomy Picture of the Day: apod.nasa.gov/apod/astropix.html. Two space scientists scour the Internet and select one beautiful astronomy image to feature each day. Their archives range widely, from images of planets and nebulae to rockets and space instruments; they also have many photos of the night sky. The search function (see the menu on the bottom of the page) works quite well for finding something specific among the many years' worth of daily images.
- Hubble Space Telescope Images: www.hubblesite.org/newscenter/archive/browse/images. Starting at this page, you can select from among hundreds of Hubble pictures by subject or by date. Note that many of the images have supporting pictures with them, such as diagrams, animations, or comparisons. Excellent captions and background information are provided. Other ways to approach these images are through the more public-oriented Hubble Gallery (www.hubblesite.org/gallery) and the European homepage (www.spacetelescope.org/images).
- National Aeronautics and Space Administration's (NASA's) Planetary Photojournal: photojournal.jpl.nasa.gov. This site features thousands of images from planetary exploration, with captions of varied length. You can select images by world, feature name, date, or catalog number, and download images in a number of popular formats. However, only NASA mission images are included. Note the Photojournal Search option on the menu at the top of the homepage to access ways to search their archives.

Videos

Cosmic Voyage: www.youtube.com/watch?v=qxXf7AJZ73A. This video presents a portion of Cosmic Voyage, narrated by Morgan Freeman (8:34).

Powers of Ten: www.youtube.com/watch?v=0fKBhvDjuy0. This classic short video is a much earlier version of Powers of Ten, narrated by Philip Morrison (9:00).

The Known Universe: www.youtube.com/watch?v=17jymDn0W6U. This video tour from the American Museum of Natural History has realistic animation, music, and captions (6:30).

Wanderers: apod.nasa.gov/apod/ap141208.html. This video provides a tour of the solar system, with narrative by Carl Sagan, imagining other worlds with dramatically realistic paintings (3:50).

EXERCISES

1. (a) If it takes light about 8 minutes to travel from the Sun to Earth, how long does it take light to reach Earth from Neptune, which is 30 times as far from us? (b) What does this mean for a two-way conversation between Earth and a spacecraft orbiting Neptune using radio waves?

2. Since most of the math you need for this class consists of ratios, you may find that you already have a platform from which to venture forth by making a list of five different proportionalities (ratios) from your daily life.

3. (a) Write the following numbers in scientific notation (see Appendix C if you are unfamiliar with this notation): 100; 0.011; 101; 1,000,000,000,000,000; 6378; and 0.000654. (b) Write the following numbers in “normal" numerical form: 3.14×10^2; 3.14×10^1; 3.14×10^0; 3.14×10^{-1}; and 3.14×10^{-2}. (c) Calculate $2 \times 10^2 + 1 \times 10^{-1}$; $\left(2.18 \times 10^{-18} J\right) / \left(6.63 \times 10^{-34} Js\right)$; and $\left(9.11 \times 10^{-11} kg\right)\left(2.998 \times 10^8 m/s\right)^2$.

Derived copy of The Structure of the Atom

LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Describe the structure of atoms and the components of nuclei
- Explain the behavior of electrons within atoms and how electrons interact with light to move among energy levels

The idea that matter is composed of tiny particles called atoms is at least 25 centuries old. It took until the twentieth century, however, for scientists to invent instruments that permitted them to probe inside an atom and find that it is not, as had been thought, hard and indivisible. Instead, the atom is a complex structure composed of still smaller particles.

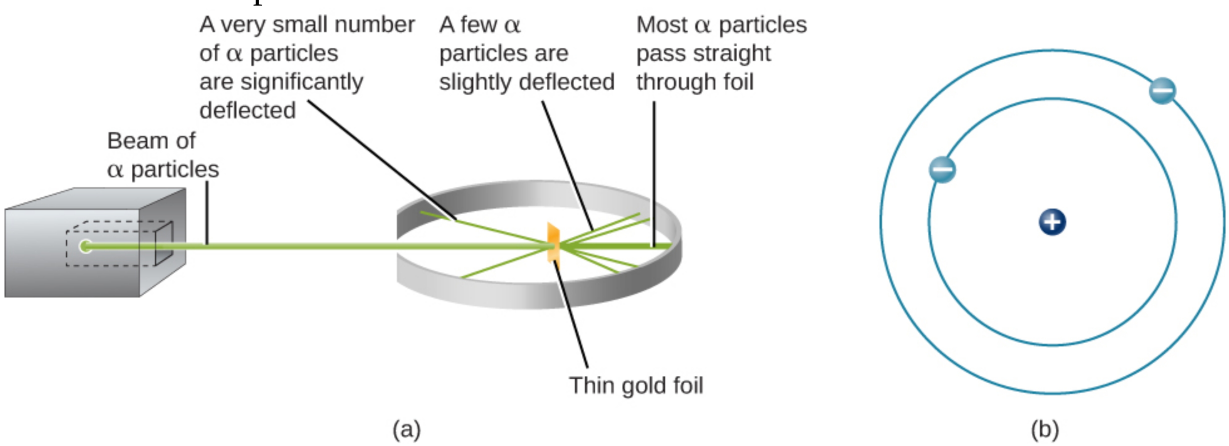
Probing the Atom

The first of these smaller particles was discovered by British physicist James (J. J.) Thomson in 1897. Named the *electron*, this particle is negatively charged. (It is the flow of these particles that produces currents of electricity, whether in lightning bolts or in the wires leading to your lamp.) Because an atom in its normal state is electrically neutral, each electron in an atom must be balanced by the same amount of positive charge.

The next step was to determine where in the atom the positive and negative charges are located. In 1911, British physicist Ernest Rutherford devised an experiment that provided part of the answer to this question. He bombarded an extremely thin piece of gold foil, only about 400 atoms thick, with a beam of alpha particles ([link]). *Alpha particles* (α particles) are helium atoms that

have lost their electrons and thus are positively charged. Most of these particles passed though the gold foil just as if it and the atoms in it were nearly empty space. About 1 in 8000 of the alpha particles, however, completely reversed direction and bounced backward from the foil. Rutherford wrote, “It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

Rutherford’s Experiment.



(a) When Rutherford allowed α particles from a radioactive source to strike a target of gold foil, he found that, although most of them went straight through, some rebounded back in the direction from which they came. (b) From this experiment, he concluded that the atom must be constructed like a miniature solar system, with the positive charge concentrated in the nucleus and the negative charge orbiting in the large volume around the nucleus. Note that this drawing is not to scale; the electron orbits are much larger relative to the size of the nucleus.

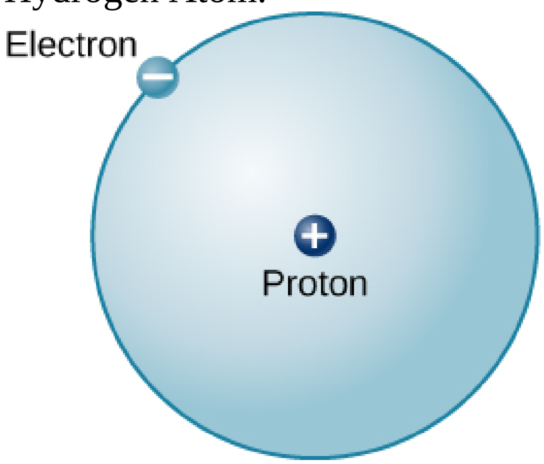
The only way to account for the particles that reversed direction when they hit the gold foil was to assume that nearly all of the mass, as well as all of the positive charge in each individual gold atom, is concentrated in a tiny center or **nucleus**. When a positively charged alpha particle strikes a nucleus, it reverses direction, much as a cue ball reverses direction when it strikes another billiard ball. Rutherford’s model placed the other type of charge—the negative electrons—in orbit around this nucleus.

Rutherford’s model required that the electrons be in motion. Positive and negative charges attract each other, so stationary electrons would fall into the positive nucleus. Also, because both the electrons and the nucleus are extremely small, most of the atom is empty, which is why nearly all of Rutherford’s particles were able to pass right through the gold foil without colliding with anything. Rutherford’s model was a very successful explanation of the experiments he conducted, although eventually scientists would discover that even the nucleus itself has structure.

The Atomic Nucleus

The simplest possible atom (and the most common one in the Sun and stars) is hydrogen. The nucleus of ordinary hydrogen contains a single proton. Moving around this proton is a single electron. The mass of an electron is nearly 2000 times smaller than the mass of a proton; the electron carries an amount of charge exactly equal to that of the proton but opposite in sign ([link]). Opposite charges attract each other, so it is an electromagnetic force that holds the proton and electron together, just as gravity is the force that keeps planets in orbit around the Sun.

Hydrogen Atom.

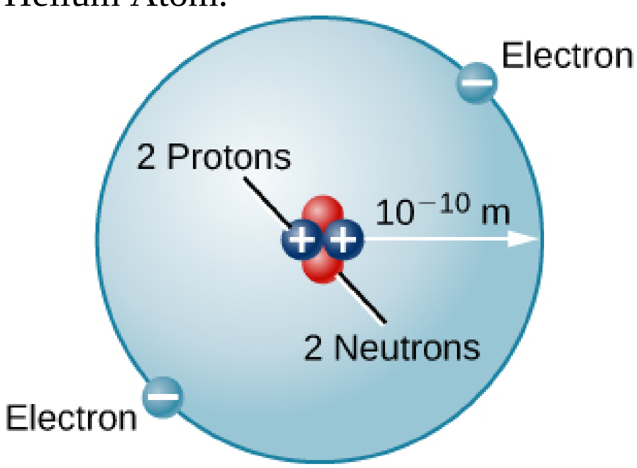


This is a schematic diagram of a hydrogen atom in its lowest energy state, also called the ground state. The proton and electron have equal but opposite charges, which exert an

electromagnetic force that binds the hydrogen atom together. In the illustration, the size of the particles is exaggerated so that you can see them; they are not to scale. They are also shown much closer than they would actually be as it would take more than an entire page to show their actual distance to scale.

There are many other types of atoms in nature. Helium, for example, is the second-most abundant element in the Sun. Helium has two protons in its nucleus instead of the single proton that characterizes hydrogen. In addition, the helium nucleus contains two neutrons, particles with a mass comparable to that of the proton but with no electric charge. Moving around this nucleus are two electrons, so the total net charge of the helium atom is also zero ([link]).

Helium Atom.



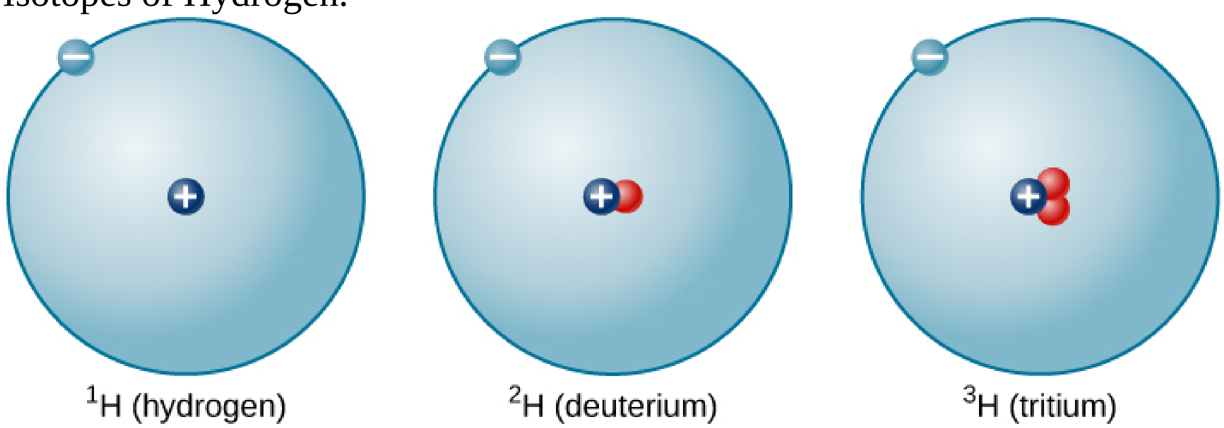
Here we see a schematic diagram of a helium atom in its lowest energy state. Two protons are present in the nucleus of all helium atoms. In the most common variety

of helium, the nucleus also contains two neutrons, which have nearly the same mass as the proton but carry no charge. Two electrons orbit the nucleus.

From this description of hydrogen and helium, perhaps you have guessed the pattern for building up all the elements (different types of atoms) that we find in the universe. The type of element is determined by the number of protons in the nucleus of the atom. For example, any atom with six protons is the element carbon, with eight protons is oxygen, with 26 is iron, and with 92 is uranium. On Earth, a typical atom has the same number of electrons as protons, and these electrons follow complex orbital patterns around the nucleus. Deep inside stars, however, it is so hot that the electrons get loose from the nucleus and (as we shall see) lead separate yet productive lives.

The ratio of neutrons to protons increases as the number of protons increases, but each element is unique. The number of neutrons is not necessarily the same for all atoms of a given element. For example, most hydrogen atoms contain no neutrons at all. There are, however, hydrogen atoms that contain one proton and one neutron, and others that contain one proton and two neutrons. The various types of hydrogen nuclei with different numbers of neutrons are called **isotopes** of hydrogen ([link]), and all other elements have isotopes as well. You can think of isotopes as siblings in the same element "family"—closely related but with different characteristics and behaviors.

Isotopes of Hydrogen.



A single proton in the nucleus defines the atom to be hydrogen, but there may be zero, one, or two neutrons. The most common isotope of hydrogen is the one with only a single proton and no neutrons.

Note:
To explore the structure of atoms, go to the PhET Build and Atom website where you can add protons, neutrons, or electrons to a model and the name of the element you have created will appear. You can also see the net charge, the mass number, whether it is stable or unstable, and whether it is an ion or a neutral atom.

The Bohr Atom

Rutherford’s model for atoms has one serious problem. Maxwell’s theory of electromagnetic radiation says that when electrons change either speed or the direction of motion, they must emit energy. Orbiting electrons constantly change their direction of motion, so they should emit a constant stream of energy. Applying Maxwell’s theory to Rutherford’s model, all electrons should spiral into the nucleus of the atom as they lose energy, and this collapse should happen very quickly—in about 10^{-16} seconds.

It was Danish physicist Niels Bohr (1885–1962) who solved the mystery of how electrons remain in orbit. He was trying to develop a model of the atom that would also explain certain regularities observed in the spectrum of hydrogen. He suggested that the spectrum of hydrogen can be understood if we assume that orbits of only certain sizes are possible for the electron. Bohr further assumed that as long as the electron moves in only one of these allowed orbits, it radiates no energy: its energy would change only if it moved from one orbit to another.

This suggestion, in the words of science historian Abraham Pais, was “one of the most audacious hypotheses ever introduced in physics.” If something equivalent were at work in the everyday world, you might find that, as you

went for a walk after astronomy class, nature permitted you to walk two steps per minute, five steps per minute, and 12 steps per minute, but no speeds in between. No matter how you tried to move your legs, only certain walking speeds would be permitted. To make things more bizarre, it would take no effort to walk at any one of the allowed speeds, but it would be difficult to change from one speed to another. Luckily, no such rules apply at the level of human behavior. But at the microscopic level of the atom, experiment after experiment has confirmed the validity of Bohr's strange idea. Bohr's suggestions became one of the foundations of the new (and much more sophisticated) model of the subatomic world called quantum mechanics.

In Bohr's model, if the electron moves from one orbit to another closer to the atomic nucleus, it must give up some energy in the form of electromagnetic radiation. If the electron goes from an inner orbit to one farther from the nucleus, however, it requires some additional energy. One way to obtain the necessary energy is to absorb electromagnetic radiation that may be streaming past the atom from an outside source.

A key feature of Bohr's model is that each of the permitted electron orbits around a given atom has a certain energy value; we therefore can think of each orbit as an **energy level**. To move from one orbit to another (which will have its own specific energy value) requires a change in the electron's energy—a change determined by the difference between the two energy values. If the electron goes to a lower level, the energy difference will be given off; if the electron goes to a higher level, the energy difference must be obtained from somewhere else. Each jump (or transition) to a different level has a fixed and definite energy change associated with it.

A crude analogy for this situation might be life in a tower of luxury apartments where the rent is determined by the quality of the view. Such a building has certain, definite numbered levels or floors on which apartments are located. No one can live on floor 5.37 or 22.5. In addition, the rent gets higher as you go up to higher floors. If you want to exchange an apartment on the twentieth floor for one on the second floor, you will not owe as much rent. However, if you want to move from the third floor to the twenty-fifth floor, your rent will increase. In an atom, too, the "cheapest" place for an electron to live is the lowest possible level, and energy is required to move to a higher level.

Here we have one of the situations where it is easier to think of electromagnetic radiation as particles (photons) rather than as waves. As electrons move from one level to another, they give off or absorb little packets of energy. When an electron moves to a higher level, it absorbs a photon of just the right energy (provided one is available). When it moves to a lower level, it emits a photon with the exact amount of energy it no longer needs in its “lower-cost living situation.”

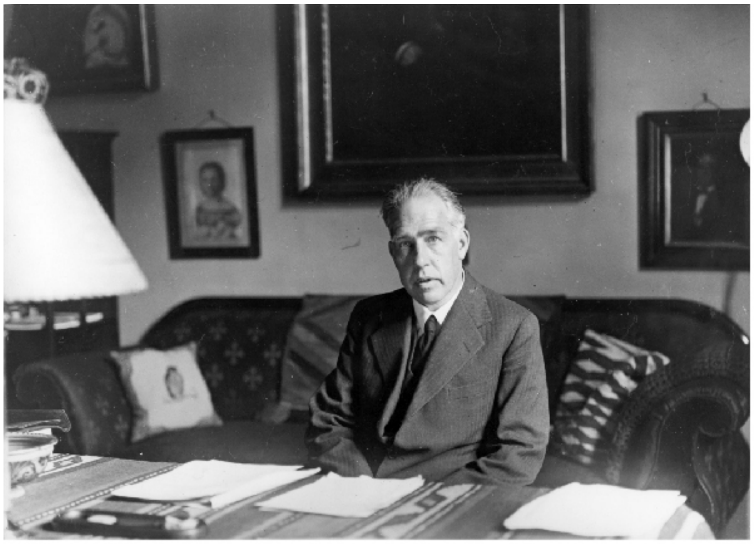
The photon and wave perspectives must be equivalent: light is light, no matter how we look at it. Thus, each photon carries a certain amount of energy that is proportional to the frequency (f) of the wave it represents. The value of its energy (E) is given by the formula
Equation:

$$E = hf$$

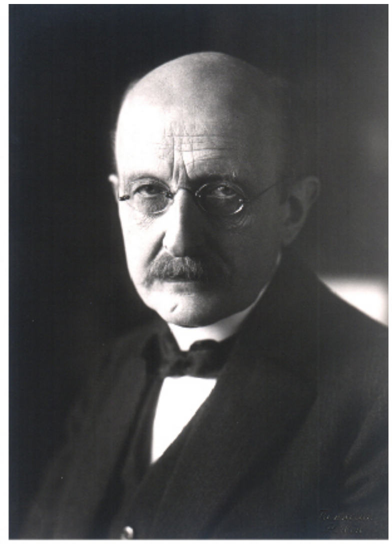
where the constant of proportionality, h, is called Planck’s constant.

The constant is named for Max Planck, the German physicist who was one of the originators of the quantum theory (Figure 5.18). If metric units are used (that is, if energy is measured in joules and frequency in hertz), then Planck’s constant has the value $h = 6.626 \times 10^{-34}$ joule-seconds (J-s). Higher-energy photons correspond to higher-frequency waves (which have a shorter wavelength); lower-energy photons are waves of lower frequency.

For atomic transitions and high energy radiation, energies are more often expressed in terms of electron volts (eV), related to joules by $1\,\text{eV} = 1.602 \times 10^{-19}\text{J}$, so that Planck’s constant may also be expressed as $h = 4.135 \times 10^{-15}\,\text{eVs}$. Elementary particle masses are usually given as their rest energy expressed in millions or billions of electron volts (MeV or GeV) divided by the speed of light squared, inverting Einstein’s famous equation $m = E_0/c^2$. The invariant mass of the Higgs boson was found in 2012 to be $m_{Higgs} = 126\ \text{GeV}/\text{c}^2$ and that of the electron is $m_e = 0.511\ \text{MeV}/\text{c}^2$.
Niels Bohr (1885–1962) and Max Planck (1858–1947).



(a)



(b)

(a) Bohr, shown at his desk in this 1935 photograph, and (b) Planck helped us understand the energy behavior of photons.

To take a specific example, consider a calcium atom inside the Sun's atmosphere in which an electron jumps from a lower level to a higher level. To do this, it needs about 5×10^{-19} joules of energy, which it can conveniently obtain by absorbing a passing photon of that energy coming from deeper inside the Sun. This photon is equivalent to a wave of light whose frequency is about 7.5×10^{14} hertz and whose wavelength is about 3.9×10^{-7} meters (393 nanometers), in the deep violet part of the visible light spectrum. Although it may seem strange at first to switch from picturing light as a photon (or energy packet) to picturing it as a wave, such switching has become second nature to astronomers and can be a handy tool for doing calculations about spectra.

Example:

The Energy of a Photon

Now that we know how to calculate the wavelength and frequency of a photon, we can use this information, along with Planck's constant, to

determine how much energy each photon carries. How much energy does a red photon of wavelength 630 nm have?
Solution
First, as we learned earlier, we can find the frequency of the photon:
Equation:

$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}\,\text{m/s}}{630 \times 10^{-9}\,\text{m}} = 4.8 \times 10^{14}\,\text{Hz}$$

Next, we can use Planck’s constant to determine the energy (remember that a Hz is the same as 1/s):
Equation:

$$E = hf = \left(6.626 \times 10^{-34}\,\text{J-s}\right)\left(4.8 \times 10^{14}\,(1/\text{s})\right) = 3.2 \times 10^{-19}\,\text{J}$$

Check Your Learning
What is the energy of a yellow photon with a frequency of 5.5×10^{14} Hz?

Note:
Answer
$E = hf = \left(6.626 \times 10^{-34}\,\text{Js}\right)\left(5.5 \times 10^{14}\,\text{Hz}\right) = 3.6 \times 10^{-19}\text{J} = 2.27\ \text{eV}$

Key Concepts and Summary

Atoms consist of a nucleus containing one or more positively charged protons. All atoms except hydrogen can also contain one or more neutrons in the nucleus. Negatively charged electrons orbit the nucleus. The number of protons defines an element (hydrogen has one proton, helium has two, and so on) of the atom. Nuclei with the same number of protons but different numbers of neutrons are different isotopes of the same element. In the Bohr model of the atom, electrons on permitted orbits (or energy levels) don’t give

off any electromagnetic radiation. But when electrons go from lower levels to higher ones, they must absorb a photon of just the right energy, and when they go from higher levels to lower ones, they give off a photon of just the right energy. The energy of a photon is connected to the frequency of the electromagnetic wave it represents by Planck’s formula, $E = hf$.

Glossary

energy level
: a particular level, or amount, of energy possessed by an atom or ion above the energy it possesses in its least energetic state; also used to refer to the states of energy an electron can have in an atom

isotope
: any of two or more forms of the same element whose atoms have the same number of protons but different numbers of neutrons

nucleus (of an atom)
: the massive part of an atom, composed mostly of protons and neutrons, and about which the electrons revolve

Derived copy of The Doppler Effect

LEARNING OBJECTIVES

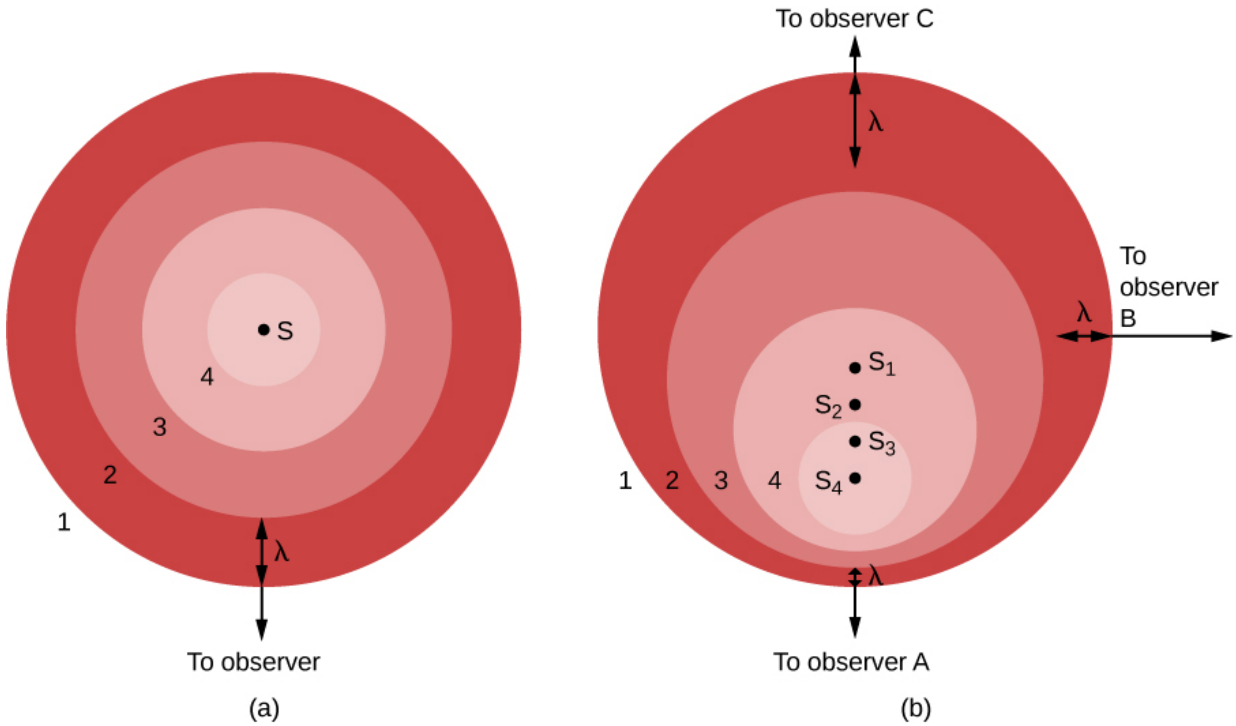
By the end of this section, you will be able to:

- Explain why the spectral lines of photons we observe from an object will change as a result of the object’s motion toward or away from us
- Describe how we can use the Doppler effect to deduce how astronomical objects are moving through space

The last two sections introduced you to many new concepts, and we hope that through those, you have seen one major idea emerge. Astronomers can learn about the elements in stars and galaxies by decoding the information in their spectral lines. There is a complicating factor in learning how to decode the message of starlight, however. If a star is moving toward or away from us, its lines will be in a slightly different place in the spectrum from where they would be in a star at rest. And most objects in the universe do have some motion relative to the Sun.

Motion Affects Waves

In 1842, Christian Doppler first measured the effect of motion on waves by hiring a group of musicians to play on an open railroad car as it was moving along the track. He then applied what he learned to all waves, including light, and pointed out that if a light source is approaching or receding from the observer, the light waves will be, respectively, crowded more closely together or spread out. The general principle, now known as the **Doppler effect**, is illustrated in [link].
Doppler Effect.



(a) A source, S, makes waves whose numbered crests (1, 2, 3, and 4) wash over a stationary observer. (b) The source S now moves toward observer *A* and away from observer *C*. Wave crest 1 was emitted when the source was at position S4, crest 2 at position S2, and so forth. Observer *A* sees waves compressed by this motion and sees a blueshift (if the waves are light). Observer *C* sees the waves stretched out by the motion and sees a redshift. Observer *B*, whose line of sight is perpendicular to the source's motion, sees no change in the waves (and feels left out).

In part (a) of the figure, the light source (S) is at rest with respect to the observer. The source gives off a series of waves, whose crests we have labeled 1, 2, 3, and 4. The light waves spread out evenly in all directions, like the ripples from a splash in a pond. The crests are separated by a distance, λ, where λ is the wavelength. The observer, who happens to be located in the direction of the bottom of the image, sees the light waves coming nice and evenly, one wavelength apart. Observers located anywhere else would see the same thing.

On the other hand, if the source of light is moving with respect to the observer, as seen in part (b), the situation is more complicated. Between the time one crest is emitted and the next one is ready to come out, the source has moved a bit, toward the bottom of the page. From the point of view of observer *A*, this motion of the source has decreased the distance between crests—it's squeezing the crests together, this observer might say.

In part (b), we show the situation from the perspective of three observers. The source is seen in four positions, S_1, S_2, S_3, and S_4, each corresponding to the emission of one wave crest. To observer *A*, the waves seem to follow one another more closely, at a decreased wavelength and thus increased frequency. (Remember, all light waves travel at the speed of light through empty

space, no matter what. This means that motion cannot affect the speed, but only the wavelength and the frequency. As the wavelength decreases, the frequency must increase. If the waves are shorter, more will be able to move by during each second.)

The situation is not the same for other observers. Let's look at the situation from the point of view of observer *C*, located opposite observer *A* in the figure. For her, the source is moving away from her location. As a result, the waves are not squeezed together but instead are spread out by the motion of the source. The crests arrive with an increased wavelength and decreased frequency. To observer *B*, in a direction at right angles to the motion of the source, no effect is observed. The wavelength and frequency remain the same as they were in part (a) of the figure.

We can see from this illustration that the Doppler effect is produced only by a motion toward or away from the observer, a motion called **radial velocity**. Sideways motion does not produce such an effect. Observers between *A* and *B* would observe some shortening of the light waves for that part of the motion of the source that is along their line of sight. Observers between *B* and *C* would observe lengthening of the light waves that are along their line of sight.

You may have heard the Doppler effect with sound waves. When a train whistle or police siren approaches you and then moves away, you will notice a decrease in the pitch (which is how human senses interpret sound wave frequency) of the sound waves. Compared to the waves at rest, they have changed from slightly more frequent when coming toward you, to slightly less frequent when moving away from you.

Note:
A nice example of this change in the sound of a train whistle can be heard at the end of the classic Beach Boys song "Caroline, No" on their album *Pet Sounds*. To hear this sound, go to this YouTube version of the song. The sound of the train begins at approximately 2:20.

Color Shifts

When the source of waves moves toward you, the wavelength decreases a bit. If the waves involved are visible light, then the colors of the light change slightly. As wavelength decreases, they shift toward the blue end of the spectrum: astronomers call this a *blueshift* (since the end of the spectrum is really violet, the term should probably be *violetshift*, but blue is a more common color). When the source moves away from you and the wavelength gets longer, we call the change in colors a *redshift*. Because the Doppler effect was first used with visible light in astronomy, the terms "blueshift" and "redshift" became well established. Today, astronomers use these words to describe changes in the wavelengths of radio waves or X-rays as comfortably as they use them to describe changes in visible light.

The greater the motion toward or away from us, the greater the Doppler shift. If the relative motion is entirely along the line of sight, the formula for the Doppler shift of light is
Equation:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

where λ is the wavelength emitted by the source, Δλ is the difference between λ and the wavelength measured by the observer, *c* is the speed of light, and *v* is the relative speed of the observer and the source in the line of sight. The variable *v* is counted as positive if the velocity is one of recession, and negative if it is one of approach. Solving this equation for the velocity, we find $v = c \times \Delta\lambda/\lambda$.

If a star approaches or recedes from us, the wavelengths of light in its continuous spectrum appear shortened or lengthened, respectively, as do those of the dark lines. However, unless its speed is tens of thousands of kilometers per second, the star does not appear noticeably bluer or redder than normal. The Doppler shift is thus not easily detected in a continuous spectrum and cannot be measured accurately in such a spectrum. The wavelengths of the absorption lines can be measured accurately, however, and their Doppler shift is relatively simple to detect.

Example:

The Doppler Effect

We can use the Doppler effect equation to calculate the radial velocity of an object if we know three things: the speed of light, the original (unshifted) wavelength of the light emitted, and the difference between the wavelength of the emitted light and the wavelength we observe. For particular absorption or emission lines, we usually know exactly what wavelength the line has in our laboratories on Earth, where the source of light is not moving. We can measure the new wavelength with our instruments at the telescope, and so we know the difference in wavelength due to Doppler shifting. Since the speed of light is a universal constant, we can then calculate the radial velocity of the star.

A particular emission line of hydrogen is originally emitted with a wavelength of 656.3 nm from a gas cloud. At our telescope, we observe the wavelength of the emission line to be 656.6 nm. How fast is this gas cloud moving toward or away from Earth?

Solution

Because the light is shifted to a longer wavelength (redshifted), we know this gas cloud is moving away from us. The speed can be calculated using the Doppler shift formula:

Deleted a buggy equation that would not allow the print preview function to work.

Check Your Learning

Suppose a spectral line of hydrogen, normally at 500 nm, is observed in the spectrum of a star to be at 500.1 nm. How fast is the star moving toward or away from Earth?

Note:

Answer:

Because the light is shifted to a longer wavelength, the star is moving away from us:

$$\nu = c \times \frac{\Delta\lambda}{\lambda} = \left(3.0 \times 10^8\,\text{m/s}\right)\left(\frac{0.1\,\text{nm}}{500\,\text{nm}}\right) = \left(3.0 \times 10^8\,\text{m/s}\right)\left(\frac{0.1 \times 10^{-9}\,\text{m}}{500 \times 10^{-9}\,\text{m}}\right) = 60{,}000\,\text{m/s}.$$

Its speed is
60,000 m/s.

You may now be asking: if all the stars are moving and motion changes the wavelength of each spectral line, won’t this be a disaster for astronomers trying to figure out what elements are present in the stars? After all, it is the precise wavelength (or color) that tells astronomers which lines belong to which element. And we first measure these wavelengths in containers of gas in our laboratories, which are not moving. If every line in a star’s spectrum is now shifted by its motion to a different wavelength (color), how can we be sure which lines and which elements we are looking at in a star whose speed we do not know?

Take heart. This situation sounds worse than it really is. Astronomers rarely judge the presence of an element in an astronomical object by a single line. It is the *pattern* of lines unique to hydrogen or calcium that enables us to determine that those elements are part of the star or galaxy we are observing. The Doppler effect does not change the pattern of lines from a given element—it only shifts the whole pattern slightly toward redder or bluer wavelengths. The shifted pattern is still quite easy to recognize. Best of all, when we do recognize a familiar element’s pattern, we get a bonus: the amount the pattern is shifted can enable us to determine the speed of the objects in our line of sight.

The training of astronomers includes much work on learning to decode light (and other electromagnetic radiation). A skillful “decoder” can learn the temperature of a star, what elements are in it, and even its speed in a direction toward us or away from us. That’s really an impressive amount of information for stars that are light-years away.

Key Concepts and Summary

If an atom is moving toward us when an electron changes orbits and produces a spectral line, we see that line shifted slightly toward the blue of its normal wavelength in a spectrum. If the atom is moving away, we see the line shifted toward the red. This shift is known as the Doppler effect and can be used to measure the radial velocities of distant objects.

For Further Exploration

Articles

Augensen, H. & Woodbury, J. “The Electromagnetic Spectrum.” *Astronomy* (June 1982): 6.

Darling, D. “Spectral Visions: The Long Wavelengths.” *Astronomy* (August 1984): 16; “The Short Wavelengths.” *Astronomy* (September 1984): 14.

Gingerich, O. “Unlocking the Chemical Secrets of the Cosmos.” *Sky & Telescope* (July 1981): 13.

Stencil, R. et al. “Astronomical Spectroscopy.” *Astronomy* (June 1978): 6.

Websites

Doppler Effect: http://www.physicsclassroom.com/class/waves/Lesson-3/The-Doppler-Effect. A shaking bug and the Doppler Effect explained.

Electromagnetic Spectrum: http://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html. An introduction to the electromagnetic spectrum from NASA's *Imagine the Universe*; note that you can click the "Advanced" button near the top and get a more detailed discussion.

Rainbows: How They Form and How to See Them: http://www.livescience.com/30235-rainbows-formation-explainer.html. By meteorologist and amateur astronomer Joe Rao.

Videos

Doppler Effect: http://www.esa.int/spaceinvideos/Videos/2014/07/Doppler_effect_-_classroom_demonstration_video_VP05. ESA video with Doppler ball demonstration and Doppler effect and satellites (4:48).

How a Prism Works to Make Rainbow Colors: https://www.youtube.com/watch?v=JGqsi_LDUn0. Short video on how a prism bends light to make a rainbow of colors (2:44).

Tour of the Electromagnetic Spectrum: https://www.youtube.com/watch?v=HPcAWNlVl-8. *NASA Mission Science* video tour of the bands of the electromagnetic spectrum (eight short videos).

Introductions to Quantum Mechanics

Ford, Kenneth. *The Quantum World.* 2004. A well-written recent introduction by a physicist/educator.

Gribbin, John. *In Search of Schroedinger's Cat.* 1984. Clear, very basic introduction to the fundamental ideas of quantum mechanics, by a British physicist and science writer.

Rae, Alastair. *Quantum Physics: A Beginner's Guide.* 2005. Widely praised introduction by a British physicist.

Collaborative Group Activities

A. Have your group make a list of all the electromagnetic wave technology you use during a typical day.
B. How many applications of the Doppler effect can your group think of in everyday life? For example, why would the highway patrol find it useful?
C. Have members of your group go home and "read" the face of your radio set and then compare notes. If you do not have a radio, research "broadcast radio frequencies" to find answers to the following questions. What do all the words and symbols mean? What

frequencies can your radio tune to? What is the frequency of your favorite radio station? What is its wavelength?

D. If your instructor were to give you a spectrometer, what kind of spectra does your group think you would see from each of the following: (1) a household lightbulb, (2) the Sun, (3) the “neon lights of Broadway,” (4) an ordinary household flashlight, and (5) a streetlight on a busy shopping street?
E. Suppose astronomers want to send a message to an alien civilization that is living on a planet with an atmosphere very similar to that of Earth’s. This message must travel through space, make it through the other planet’s atmosphere, and be noticeable to the residents of that planet. Have your group discuss what band of the electromagnetic spectrum might be best for this message and why. (Some people, including noted physicist Stephen Hawking, have warned scientists not to send such messages and reveal the presence of our civilization to a possible hostile cosmos. Do you agree with this concern?)

Review Questions

Exercise:

Problem:

What distinguishes one type of electromagnetic radiation from another? What are the main categories (or bands) of the electromagnetic spectrum?

Exercise:

Problem: What is a wave? Use the terms *wavelength* and *frequency* in your definition.

Exercise:

Problem:

Is your textbook the kind of idealized object (described in section on radiation laws) that absorbs all the radiation falling on it? Explain. How about the black sweater worn by one of your classmates?

Exercise:

Problem: Where in an atom would you expect to find electrons? Protons? Neutrons?

Exercise:

Problem:

Explain how emission lines and absorption lines are formed. In what sorts of cosmic objects would you expect to see each?

Exercise:

Problem:

Explain how the Doppler effect works for sound waves and give some familiar examples.

Exercise:

Problem: What kind of motion for a star does not produce a Doppler effect? Explain.

Exercise:

Problem: Describe how Bohr’s model used the work of Maxwell.

Exercise:

Problem: Explain why light is referred to as electromagnetic radiation.

Exercise:

Problem:

Explain the difference between radiation as it is used in most everyday language and radiation as it is used in an astronomical context.

Exercise:

Problem: What are the differences between light waves and sound waves?

Exercise:

Problem:

Which type of wave has a longer wavelength: AM radio waves (with frequencies in the kilohertz range) or FM radio waves (with frequencies in the megahertz range)? Explain.

Exercise:

Problem:

Explain why astronomers long ago believed that space must be filled with some kind of substance (the “aether”) instead of the vacuum we know it is today.

Exercise:

Problem: Explain what the ionosphere is and how it interacts with some radio waves.

Exercise:

Problem: Which is more dangerous to living things, gamma rays or X-rays? Explain.

Exercise:

Problem:

Explain why we have to observe stars and other astronomical objects from above Earth’s atmosphere in order to fully learn about their properties.

Exercise:

Problem:

Explain why hotter objects tend to radiate more energetic photons compared to cooler objects.

Exercise:

Problem: Explain how we can deduce the temperature of a star by determining its color.

Exercise:

Problem:

Explain what dispersion is and how astronomers use this phenomenon to study a star's light.

Exercise:

Problem: Explain why glass prisms disperse light.

Exercise:

Problem: Explain what Joseph Fraunhofer discovered about stellar spectra.

Exercise:

Problem:

Explain how we use spectral absorption and emission lines to determine the composition of a gas.

Exercise:

Problem:

Explain the results of Rutherford's gold foil experiment and how they changed our model of the atom.

Exercise:

Problem:

Is it possible for two different atoms of carbon to have different numbers of neutrons in their nuclei? Explain.

Exercise:

Problem: What are the three isotopes of hydrogen, and how do they differ?

Exercise:

Problem:

Explain how electrons use light energy to move among energy levels within an atom.

Exercise:

Problem:

Explain why astronomers use the term “blueshifted” for objects moving toward us and “redshifted” for objects moving away from us.

Exercise:

Problem:

If spectral line wavelengths are changing for objects based on the radial velocities of those objects, how can we deduce which type of atom is responsible for a particular absorption or emission line?

Thought Questions

Exercise:

Problem:

Make a list of some of the many practical consequences of Maxwell’s theory of electromagnetic waves (television is one example).

Exercise:

Problem: With what type of electromagnetic radiation would you observe:

A. A star with a temperature of 5800 K?
B. A gas heated to a temperature of one million K?
C. A person on a dark night?

Exercise:

Problem:

Why is it dangerous to be exposed to X-rays but not (or at least much less) dangerous to be exposed to radio waves?

Exercise:

Problem:

Go outside on a clear night, wait 15 minutes for your eyes to adjust to the dark, and look carefully at the brightest stars. Some should look slightly red and others slightly blue. The primary factor that determines the color of a star is its temperature. Which is hotter: a blue star or a red one? Explain

Exercise:

Problem:

Water faucets are often labeled with a red dot for hot water and a blue dot for cold. Given Wien’s law, does this labeling make sense?

Exercise:

Problem:

Suppose you are standing at the exact center of a park surrounded by a circular road. An ambulance drives completely around this road, with siren blaring. How does the pitch of the siren change as it circles around you?

Exercise:

Problem:

How could you measure Earth's orbital speed by photographing the spectrum of a star at various times throughout the year? (Hint: Suppose the star lies in the plane of Earth's orbit.)

Exercise:

Problem:

Astronomers want to make maps of the sky showing sources of X-rays or gamma rays. Explain why those X-rays and gamma rays must be observed from above Earth's atmosphere.

Exercise:

Problem:

The greenhouse effect can be explained easily if you understand the laws of blackbody radiation. A greenhouse gas blocks the transmission of infrared light. Given that the incoming light to Earth is sunlight with a characteristic temperature of 5800 K (which peaks in the visible part of the spectrum) and the outgoing light from Earth has a characteristic temperature of about 300 K (which peaks in the infrared part of the spectrum), explain how greenhouse gases cause Earth to warm up. As part of your answer, discuss that greenhouse gases block both incoming and outgoing infrared light. Explain why these two effects don't simply cancel each other, leading to no net temperature change.

Exercise:

Problem:

An idealized radiating object does not reflect or scatter any radiation but instead absorbs all of the electromagnetic energy that falls on it. Can you explain why astronomers call such an object a blackbody? Keep in mind that even stars, which shine brightly in a variety of colors, are considered blackbodies. Explain why.

Exercise:

Problem:

Why are ionized gases typically only found in very high-temperature environments?

Exercise:

Problem: Explain why each element has a unique spectrum of absorption or emission lines.

Figuring for Yourself

Exercise:

Problem:

What is the wavelength of the carrier wave of a campus radio station, broadcasting at a frequency of 97.2 MHz (million cycles per second or million hertz)?

Exercise:

Problem:

What is the frequency of a red laser beam, with a wavelength of 670 nm, which your astronomy instructor might use to point to slides during a lecture on galaxies?

Exercise:

Problem:

You go to a dance club to forget how hard your astronomy midterm was. What is the frequency of a wave of ultraviolet light coming from a blacklight in the club, if its wavelength is 150 nm?

Exercise:

Problem: What is the energy of the photon with the frequency you calculated in [link]?

Exercise:

Problem:

If the emitted infrared radiation from Pluto, has a wavelength of maximum intensity at 75,000 nm, what is the temperature of Pluto assuming it follows Wien’s law?

Exercise:

Problem:

What is the temperature of a star whose maximum light is emitted at a wavelength of 290 nm?

Exercise:

Problem:

What is the energy in electron volts of a green photon with wavelength 500-nm? An ultraviolet photon at 250-nm? A 90-MHz ($1\ \text{megahertz} = 10^6\ \text{Hz}$) radio-wave photon?

Glossary

Doppler effect

the apparent change in wavelength or frequency of the radiation from a source due to its relative motion away from or toward the observer

radial velocity

motion toward or away from the observer; the component of relative velocity that lies in the line of sight

Derived copy of The Massive Atmosphere of Venus

Why do some planets have atmospheres and others do not?

Our curiosity to know why Venus is surrounded by a heavy atmosphere while Mars goes virtually without leads us to wonder about the likelihood of atmospheres surrounding the newly discovered planets around other stars. It turns out that there is a simple heuristic for determining if a particular gas has leaked away from a planet over 4.5 Billion years: multiply the average velocity of a given type of molecule by a factor of 6, and if that is larger than the planet's escape speed, then molecules of that type will have escaped from the planet's atmosphere in significant quantities in that time. Otherwise most of it will have been retained.

The escape speed can be calculated for any planet of mass M and radius r by the relation
Equation:

$$v_e(r) = \sqrt{\frac{2GM}{r}} \ ,$$

where G is Newton's gravitational constant. We can save future tedium by finding the escape speed from the known speed for Earth, given at 11.2 km/s in Section 3.5, and the ratio of the planet's mass and radius to that of the Earth,
Equation:

$$v_e(r) = 11.2\,\mathrm{km/s}\sqrt{\frac{M}{M_E}\,\frac{r_E}{r}} \ .$$

For instance, for Mercury,
Equation:

$$v_e(r) = 11.2\,\mathrm{km/s}\sqrt{\frac{0.055M_E}{M_E}\,\frac{r_E}{0.38r_E}} = 11.2\,\mathrm{km/s}\sqrt{0.14} = 11.2\,\mathrm{km/s} \times 0.38 = 4.26\,\mathrm{km/s}$$

So is this more than six times the average velocity of hydrogen molecules H_2 or not?

For the answer, we turn to Ludwig Boltzmann (1844-1906) who said that the average kinetic energy of a molecule can be expressed in terms of the temperature. Put more fundamentally, temperature is simply an expression of how fast molecules move. The temperature at which they do not move at all is

defined as zero on the Kelvin scale (0 K = - 273° C = - 459° F). Boltzmann defined a constant **k** such that the following definition of temperature **T** holds for the molecule's mass **m** and velocity **v** : The average kinetic energy is

Equation:

$$\frac{1}{2} m v^2_{average} = \frac{3}{2} kT \ .$$

But what average temperature should we use for hydrogen in the Earth's atmosphere? Figure 8.12. shows that the temperature at the surface of the Earth is about 300 K, so the average velocity for the hydrogen molecule H_2 is

Equation:

$$\begin{aligned} v_{average} &= \sqrt{3}\sqrt{\frac{kT}{m_{H_2}}} = 1.73 \times \sqrt{\frac{1.38 \times 10^{-23} \ \mathrm{J/K} \times 300 \ \mathrm{K}}{3.35 \times 10^{-27}\,\mathrm{kg}} \times \frac{\mathrm{Nm}}{\mathrm{J}} \times \frac{\mathrm{kg} \ \ \mathrm{m/s^2}}{\mathrm{N}}} \\ &= 1.73 \times \sqrt{1.24 \times 10^6 \ \mathrm{m^2 s^{-2}}} = 1.73 \times \ 1.11 \ \mathrm{km/s} = 1.92 \ \mathrm{km/s} \ . \end{aligned}$$

A distribution of velocities would range from 10% of this value to 10 times this value. That is, some small fraction of hydrogen molecules of would be moving at 20 km/s, more than the Earth's escape velocity, and given a few billion years, this small fraction can add up to significant loss.

Our heuristic says to multiply the average velocity of hydrogen molecules H_2, 2 km/s, by a factor of 6, and this 12 km/s is indeed larger than the Earth’s escape speed of 11.2 km/s so we would expect that very little H_2 remains in Earth’s atmosphere, as is the case. For any other gas, we can avoid the above complexity by using a ratio of its weight to that of molecular hydrogen, which – having two hydrogen atoms – has an molecular mass of 2 atomic units. One atom of normal oxygen has 8 protons and 8 neutrons (written in shorthand as $^8O^{16}$). Each of these 16 nucleons has about the same mass as the single-proton nucleus of one hydrogen atom (and the eight electrons have negligible mass). Then the O $_2$ molecule is a pair of $^8O^{16}$ atoms with 16 times the mass of a pair of hydrogen atoms, H_2.

Thus, the average molecular velocity for O_2 is

Equation:

$$v_{average} = 2\,\mathrm{km/s}\sqrt{\frac{T}{300K}\frac{m_{H_2}}{m}} = 2\,\mathrm{km/s}\sqrt{\frac{300K}{300K}\frac{m_{H_2}}{16\,m_{H_2}}} = 2\,\mathrm{km/s}\frac{1}{4} = 0.5\,\mathrm{km/s} \ .$$

We multiply this 0.5 km/s average molecular velocity for O_2 by 6 under our heuistic and we see that the resulting 3 km/s is less than the escape velocity, so the Earth should have retained O_2 in the time since the Solar System formed. Did it?

For any other planet we can use the ratio of its surface temperature to that of Earth. On Mercury the surface temperature varies greatly from daytime 700 K to 100 K at night. But since Mercury’s day is 58.6 Earth days long, the long hot daytime temperature will be the one in play rather than an average of 300 K.

Thus, for O_2 molecules,

Equation:

$$v_{average} = 2\,\mathrm{km/s}\sqrt{\frac{T}{300K}\,\frac{m_{H_2}}{m}} = 2\,\mathrm{km/s}\sqrt{\frac{700K}{300K}\,\frac{m_{H_2}}{16\,m_{H_2}}} = 2\,\mathrm{km/s} \times 0.38 = 0.76\,\mathrm{km/s}$$

We multiply this 0.76 km/s average molecular velocity for O_2 on Mercury by 6 under our heuistic and we see that the resulting 4.6 km/s is more than Mercury's escape velocity of 4.3 km/s, so the Mercury should have lost its O_2 in the time since the Solar System formed (and, of course the lighter hydrogen).

Derived copy of Divergent Planetary Evolution

LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Compare the planetary evolution of Venus, Earth, and Mars

Venus, Mars, and our own planet Earth form a remarkably diverse triad of worlds. Although all three orbit in roughly the same inner zone around the Sun and all apparently started with about the same chemical mix of silicates and metals, their evolutionary paths have diverged. As a result, Venus became hot and dry, Mars became cold and dry, and only Earth ended up with what we consider a hospitable climate.

We have discussed the runaway greenhouse effect on Venus and the runaway refrigerator effect on Mars, but we do not understand exactly what started these two planets down these separate evolutionary paths. Was Earth ever in danger of a similar fate? Or might it still be diverted onto one of these paths, perhaps due to stress on the atmosphere generated by human pollutants? One of the reasons for studying Venus and Mars is to seek insight into these questions.

Some people have even suggested that if we understood the evolution of Mars and Venus better, we could possibly reverse their evolution and restore more earthlike environments. While it seems unlikely that humans could ever make either Mars or Venus into a replica of Earth, considering such possibilities is a useful part of our more general quest to understand the delicate environmental balance that distinguishes our planet from its

two neighbors. In Cosmic Samples and the Origin of the Solar System, we return to the comparative study of the terrestrial planets and their divergent evolutionary histories.

Key Concepts and Summary

Earth, Venus, and Mars have diverged in their evolution from what may have been similar beginnings. We need to understand why if we are to protect the environment of Earth.

For Further Exploration

Articles

Venus

Dorminey, B. “Cool Science on a Hot World.” *Astronomy* (February 2006): 46. Five-page overview of Venus and the Venus Express mission plans.

Kargel, J. “Rivers of Venus.” *Sky & Telescope* (August 1997): 32. On lava channels.

Robertson, D. “Parched Planet.” *Sky & Telescope* (April 2008): 26. Overview of our understanding of the planet.

Robinson, C. “Magellan Reveals Venus.” *Astronomy* (February 1995): 32.

Stofan, E. “The New Face of Venus.” *Sky & Telescope* (August 1993): 22.

Zimmerman, R. “Taking Venus by Storm.” *Astronomy* (October 2008): 66. On results from the Venus Express mission.

Mars

Albee, A. “The Unearthly Landscapes of Mars.” *Scientific American* (June 2003): 44. Results from the Mars Global Surveyor and Mars Odyssey missions and an overview.

Bell, J. “A Fresh Look at Mars.” *Astronomy* (August 2015): 28. Nice summary of recent spacecraft results and how they are revising our understanding of Mars.

Bell, J. “Uncovering Mars’ Secret Past.” *Sky & Telescope* (July 2009): 22. How rovers and orbiters are helping us to understand Mars history and the role of water.

Bell, J. “The Red Planet’s Watery Past.” *Scientific American* (December 2006): 62. Rovers are furnishing proof that ancient Mars was wet.

Burnham, R. “Red Planet Rendezvous.” *Astronomy* (May 2006): 68. About Mariner Valley and a flyover film constructed from many still images.

Christensen, P. “The Many Faces of Mars.” *Scientific American* (July 2005): 32. Results from the Rover mission; evidence that Mars was once wet in places.

Lakdawalla, E. “The History of Water on Mars.” *Sky & Telescope* (September 2013): 16. Clear review of our current understanding of the role of water on Mars in different epochs.

Malin, M. “Visions of Mars.” *Sky & Telescope* (April 1999): 42. A geological tour of the red planet, with new Mars Global Surveyor images.

McEwen, A. “Mars in Motion.” *Scientific American* (May 2013): 58. On gullies and other surface changes.

McKay, C. & Garcia, V. “How to Search for Life on Mars.” *Scientific American* (June 2014): 44. Experiments future probes could perform.

Naeye, R. “Europe’s Eye on Mars.” *Sky & Telescope* (December 2005): 30. On the Mars Express mission and the remarkable close-up images it is sending.

Talcott, R. “Seeking Ground Truth on Mars.” *Astronomy* (October 2009): 34. How rovers and orbiters are helping scientists understand the red planet’s surface.

Websites

European Space Agency Mars Express Page: http://www.esa.int/Our_Activities/Space_Science/Mars_Express.

European Space Agency Venus Express Page: http://www.esa.int/Our_Activities/Space_Science/Venus_Express.

High Resolution Imaging Science Experiment: http://hirise.lpl.arizona.edu/.

Jet Propulsion Lab Mars Exploration Page: http://mars.jpl.nasa.gov/.

Mars Globe HD app: https://itunes.apple.com/us/app/mars-globe-hd/id376020224?mt=8.

Mars Rover 360° Panorama: http://www.360cities.net/image/curiosity-rover-martian-solar-day-2#171.10,26.50,70.0. Interactive.

NASA Center for Mars Exploration: http://www.nasa.gov/mission_pages/mars/main/index.html.

NASA Solar System Exploration Mars Page: http://solarsystem.nasa.gov/planets/mars.

NASA Solar System Exploration Venus Page: http://solarsystem.nasa.gov/planets/venus.

NASA’s apps about Mars for phones and tablets can be found at: http://mars.nasa.gov/mobile/info/.

NASA’s Magellan Mission to Venus: http://www2.jpl.nasa.gov/magellan/.

Russian (Soviet) Venus Missions and Images: http://mentallandscape.com/C_CatalogVenus.htm.

Venus Atlas app: https://itunes.apple.com/us/app/venus-atlas/id317310503?mt=8.

Venus Express Results Article: http://www.mpg.de/798302/F002_Focus_026-033.pdf.

Videos

50 Years of Mars Exploration: http://www.jpl.nasa.gov/video/details.php?id=1395. NASA’s summary of all missions through *MAVEN*; good quick overview (4:08).

Being a Mars Rover: What It’s Like to be an Interplanetary Explorer: https://www.youtube.com/watch?v=nRpCOEsPD54. 2013 talk by Dr. Lori Fenton about what it’s like on the surface of Mars (1:07:24).

Magellan Maps Venus: http://www.bbc.co.uk/science/space/solarsystem/space_missions/magellan_probe#p005y07s. BBC clip with Dr. Ellen Stofan on the radar images of Venus and what they tell us (3:06).

Our *Curiosity*: https://www.youtube.com/watch?v=XczKXWvokm4. Mars *Curiosity* rover 2-year anniversary video narrated by Neil deGrasse Tyson and Felicia Day (6:01).

Planet Venus: The Deadliest Planet, Venus Surface and Atmosphere: https://www.youtube.com/watch?v=HqFVxWfVtoo. Quick tour of Venus’ atmosphere and surface (2:04).

Planetary Protection and Hitchhikers in the Solar System: The Danger of Mingling Microbes: https://www.youtube.com/watch?v=6iGC3uO7jBI. 2009 talk by Dr. Margaret Race on preventing contamination between worlds (1:28:50).

Collaborative Group Activities

A. Your group has been asked by high NASA officials to start planning the first human colony on Mars. Begin by making a list of what sorts of things humans would need to bring along to be able to survive for years on the surface of the red planet.
B. As a publicity stunt, the mayor of Venus, Texas (there really is such a town), proposes that NASA fund a mission to Venus with humans on board. Clearly, the good mayor neglected to take an astronomy course in college. Have your group assemble a list of as many reasons as possible why it is unlikely that humans will soon land on the surface of Venus.
C. Even if humans would have trouble surviving on the surface of Venus, this does not mean we could not learn a lot more about our veiled sister planet. Have your group brainstorm a series of missions (pretend cost is no object) that would provide us with more detailed information about Venus' atmosphere, surface, and interior.
D. Sometime late in the twenty-first century, when travel to Mars has become somewhat routine, a very wealthy couple asks you to plan a honeymoon tour of Mars that includes the most spectacular sights on the red planet. Constitute your group as the Percival Lowell Memorial Tourist Agency, and come up with a list of not-to-be missed tourist stops on Mars.
E. In the popular book and film, called *The Martian*, the drama really begins when our hero is knocked over and loses consciousness as he is half buried by an intense wind storm on Mars. Given what you have learned about Mars' atmosphere in this chapter, have your group discuss how realistic that scenario is. (By the way, the author of the book has himself genially acknowledged in interviews and talks that this is a reasonable question to ask.)
F. Astronomers have been puzzled and annoyed about the extensive media publicity that was given the small group of "true believers" who claimed the "Face on Mars" was not a natural formation (see the Astronomy and Pseudoscience: The "Face on Mars" feature box). Have your group make a list of the reasons many of the media were so enchanted by this story. What do you think astronomers could or

should do to get the skeptical, scientific perspective about such issues before the public?

G. Your group is a special committee of scientists set up by the United Nations to specify how any Mars samples should be returned to Earth so that possible martian microbes do not harm Earth life. What precautions would you recommend, starting at Mars and going all the way to the labs that analyze the martian samples back on Earth?
H. Have your group brainstorm about Mars in popular culture. How many movies, songs or other music, and products can you think of connected with Mars? What are some reasons that Mars would be a popular theme for filmmakers, songwriters, and product designers?

Review Questions

Exercise:

Problem:

List several ways that Venus, Earth, and Mars are similar, and several ways they are different.

Exercise:

Problem:

Compare the current atmospheres of Earth, Venus, and Mars in terms of composition, thickness (and pressure at the surface), and the greenhouse effect.

Exercise:

Problem:

How might Venus' atmosphere have evolved to its present state through a runaway greenhouse effect?

Exercise:

Problem:

Describe the current atmosphere on Mars. What evidence suggests that it must have been different in the past?

Exercise:

Problem:

Explain the runaway refrigerator effect and the role it may have played in the evolution of Mars.

Exercise:

Problem:

What evidence do we have that there was running (liquid) water on Mars in the past? What evidence is there for water coming out of the ground even today?

Exercise:

Problem:

What evidence is there that Venus was volcanically active about 300–600 million years ago?

Exercise:

Problem: Why is Mars red?

Exercise:

Problem: What is the composition of clouds on Mars?

Exercise:

Problem: What is the composition of the polar caps on Mars?

Exercise:

Problem:

Describe two anomalous features of the rotation of Venus and what might account for them.

Exercise:

Problem:

How was the *Mars Odyssey* spacecraft able to detect water on Mars without landing on it?

Thought Questions

Exercise:

Problem:

What are the advantages of using radar imaging rather than ordinary cameras to study the topography of Venus? What are the relative advantages of these two approaches to mapping Earth or Mars?

Exercise:

Problem:

Venus and Earth are nearly the same size and distance from the Sun. What are the main differences in the geology of the two planets? What might be some of the reasons for these differences?

Exercise:

Problem:

Why is there so much more carbon dioxide in the atmosphere of Venus than in that of Earth? Why so much more carbon dioxide than on Mars?

Exercise:

Problem:

If the Viking missions were such a rich source of information about Mars, why have we sent the Pathfinder, *Global Surveyor*, and other more recent spacecraft to Mars? Make a list of questions about Mars that still puzzle astronomers.

Exercise:

Problem:

Compare Mars with Mercury and the Moon in terms of overall properties. What are the main similarities and differences?

Exercise:

Problem:

Contrast the mountains on Mars and Venus with those on Earth and the Moon.

Exercise:

Problem:

We believe that all of the terrestrial planets had similar histories when it comes to impacts from space. Explain how this idea can be used to date the formation of the martian highlands, the martian basins, and the Tharsis volcanoes. How certain are the ages derived for these features (in other words, how do we check the ages we derive from this method)?

Exercise:

Problem:

Is it likely that life ever existed on either Venus or Mars? Justify your answer in each case.

Exercise:

Problem:

Suppose that, decades from now, NASA is considering sending astronauts to Mars and Venus. In each case, describe what kind of protective gear they would have to carry, and what their chances for survival would be if their spacesuits ruptured.

Exercise:

Problem:

We believe that Venus, Earth, and Mars all started with a significant supply of water. Explain where that water is now for each planet.

Exercise:

Problem:

One source of information about Mars has been the analysis of meteorites from Mars. Since no samples from Mars have ever been returned to Earth from any of the missions we sent there, how do we know these meteorites are from Mars? What information have they revealed about Mars?

Exercise:

Problem:

The runaway greenhouse effect and its inverse, the runaway refrigerator effect, have led to harsh, uninhabitable conditions on Venus and Mars. Does the greenhouse effect always cause climate changes leading to loss of water and life? Give a reason for your answer.

Exercise:

Problem:

In what way is the high surface temperature of Venus relevant to concerns about global warming on Earth today?

Exercise:

Problem:

What is a dust devil? Would you expect to feel more of a breeze from a dust devil on Mars or on Earth? Explain.

Exercise:

Problem:

Near the martian equator, temperatures at the same spot can vary from an average of –135 °C at night to an average of 30 °C during the day. How can you explain such a wide difference in temperature compared to that on Earth?

Figuring for Yourself

Exercise:

Problem:

Estimate the amount of water there could be in a global (planet-wide) region of subsurface permafrost on Mars (do the calculations for two permafrost thicknesses, 1 and 10 km, and a concentration of ice in the permafrost of 10% by volume). Compare the two results you get with the amount of water in Earth's oceans calculated in [link].

Exercise:

Problem:

At its nearest, Venus comes within about 41 million km of Earth. How distant is it at its farthest?

Exercise:

Problem:

If you weigh 150 lbs. on the surface of Earth, how much would you weigh on Venus? On Mars?

Exercise:

Problem:

Calculate the relative land area—that is, the amount of the surface not covered by liquids—of Earth, the Moon, Venus, and Mars. (Assume that 70% of Earth is covered with water.)

Exercise:

Problem:

The closest approach distance between Mars and Earth is about 56 million km. Assume you can travel in a spaceship at 58,000 km/h, which is the speed achieved by the New Horizons space probe that went to Pluto and is the fastest speed so far of any space vehicle launched from Earth. How long would it take to get to Mars at the time of closest approach?

Exercise:

Problem:

Use the heuristic that a planet will have lost a given molecule from its atmosphere over 4.5 Billion years if the average molecular speed exceeds one sixth of the planet's escape speed to calulate what Mercury's mass would have to be in order for it to still have a nitrogen atmosphere like Earth's? The molecular weight of nitrogen is 28 atomic units.